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DISCUSSION OF ENGINEERING ASPECTS OF DIFFRACTION AND REFRACTION

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By M. E. Stelzriede, and J. W. Johnson

HYDRAULICS DIVISION

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DISCUSSION

M. E. STELZRIEDE[43].—The impetus provided by World War II and the post-war interest in harbor design have resulted in a number of analytical solutions of the diffraction problem as related particularly to water waves. Three of these solutions appear to lend themselves most readily to a study of this hydrodynamic phenomenon. One theoretical approach is demonstrated by Mr. Johnson. A second is adapted from the work of P. M. Morse and P. J. Rubinstein,[44] and a third was developed by Mr. Lacombe.[45] The close agreement between the results of these independent methods is significant.

The diffraction-diagram approach illustrated by Mr. Johnson is especially useful when it is desirable to predict wave patterns over large areas of a harbor. These diagrams represent graphically the solution of W. G. Penney and A. T. Price,[46] as refined and simplified by J. A. Putnam and R. S. Arthur,[34] and by F. L. Blue, Jr., and the author.[35] The approximations applied in constructing the diagrams for the semi-infinite breakwater impose certain limitations on the use of the diagram which are generally not severe. One of these restrictions relates to the angle between the breakwater and the diffraction axis, which (as Mr. Johnson shows) should lie somewhere between the limits of 45° and 135°. The deviation of this simplified solution from the complete Penney-Price solution at short distances from the terminus is discussed by the Scripps Institution of Oceanography.[47] A good minimum limit of distance appears to be about three wave lengths; and, even at this distance, the error may become large, percentagewise, at points that lie at a large angular distance from the diffraction axis. The energy level in that area, fortunately, is very low in any case so the error in terms of absolute wave height is small.

The diffraction diagram for a breakwater gap is constructed by superposing complete Penney-Price solutions for two semi-infinite breakwaters separated by a gap of the desired width. The composite solution so obtained is no longer exact because of the influence of one arm of the breakwater on the diffractive function performed by the other. For very small openings the error in boundary conditions becomes infinite; but when the gap size is about two wave lengths or more, this error is not excessive, and, for very large openings, it is insignifi-

NOTE.—This paper by J. W. Johnson was published in March, 1952, as *Proceedings-Separate No. 122*. The numbering of footnotes and illustrations in this Separate is a continuation of the consecutive numbering used in the original paper.

[43] Research Engr., Hydr. Structures Lab., California Inst. of Technology, Pasadena, Calif.

[44] "The Diffraction of Waves by Ribbons and by Slits," by P. M. Morse and P. J. Rubinstein, *The Physical Review*, December 1, 1938, Vol. 54, pp. 895-898.

[45] "Diffraction de la Houle par une Breche," by Henri Lacombe, *Bulletin d'Information du Comité d'Oceanographie et d'Etude des Côtes, No. 2*, 4th Year, February, 1952 (published by Service Hydrographique de la Marine).

[46] "Diffraction of Sea Waves by Breakwaters," by W. G. Penney and A. T. Price, Directorate of Miscellaneous Weapons Development History No. 26, Artificial Harbors, Sec. 3D, London, England, 1944.

[34] "Diffraction of Water Waves by Breakwaters," by J. A. Putnam and R. S. Arthur, *Transactions*, Am. Geophysical Union, Vol. 29, 1948, pp. 481-490.

[35] "Diffraction of Water Waves Passing Through a Breakwater Gap," by F. L. Blue, Jr., and J. W. Johnson, *ibid.*, Vol. 30, 1949, pp. 705-718.

[47] "Application of a Solution of the Water Wave Diffraction Problem," *Wave Project Report No. 42*, Scripps Inst. of Oceanography, La Jolla, Calif., 1945.

cant. It is interesting to note that, although Mr. Johnson's diffraction diagram is for a breakwater opening that is toward the lower limit of the acceptable range, the curves agree remarkably well with those obtained from other solutions.

The Morse-Rubinstein approach to the diffraction problem was originally developed for the diffraction of electromagnetic waves by ribbons and by slits in an infinite plane,[44] and the theory has been substantially verified in the wave basin at the Hydraulic Structures Laboratory of the California Institute of Technology in Azusa. Although the solution is difficult to compute manually because of the series of Mathieu functions involved, it possesses several valuable features. The solution is exact, for example, for openings of any size, although the series converge best for very small gaps. The solution applies directly to oblique angles of approach as low as zero degrees, as well as to the condition of normal wave approach. This method determines the energy distribution leeward of the breakwater in terms of an intensity factor proportional to the square of the wave height. To find the intensity at a point whose polar coordinates are (R, ϕ) with respect to the center of a gap of given width B/L and an approach angle θ find the intensity factor corresponding to the direction of the point in question. The intensity at (R, ϕ) as a fraction of the incident wave intensity, then, is this intensity factor divided by R/L. Intensity factors have been computed and plotted[36] for openings 0.5 L, 1.0 L, 2.0 L, and 3.0 L, and for approach angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90°.

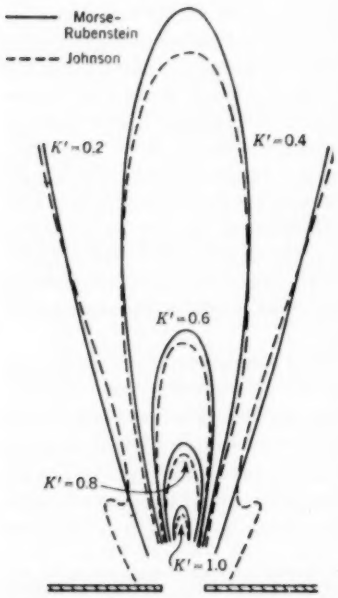

FIG. 19.—COMPARISON OF DIFFRACTION DIAGRAMS

Fig. 19 shows a comparison on a wave height basis of Mr. Johnson's diffraction diagram for a gap of 2.0 L and a similar one is derived from the Morse-Rubinstein equations. It is encouraging to note that the maximum distance between corresponding curves using the two methods is of the order of but 7% or 8% of the distance to the origin. The secondary lobes near the base of the Johnson curves appear also on the Morse-Rubinstein curves in a somewhat different direction, although they are not shown in Fig. 19.

The Lacombe solution, derived directly from Huyghens' principle and expressed in terms of trigonometric functions, appears to be easiest of all to compute. Mr. Lacombe's paper (referred to in this discussion) demonstrates the striking similarity between the Morse-Rubinstein polar intensity curves for

[36] "Diffraction of Water Waves by Breakwaters," by John H. Carr and M. E. Stelzriede, Symposium on Gravity Waves, National Bureau of Standards, Washington, D. C., June 1951.

various openings and for various approach angles, and those obtained by the Lacombe equations. For approach angles of 45° or greater the two solutions produce almost identical results. The similarity breaks down somewhat for very small approach angles and for very small gaps, but these energy curves, as Mr. Lacombe shows, exaggerate the real differences in wave height predicted by the two methods.

In the experience of the Hydraulic Structures Laboratory, it has been found that, at nominal distances from the center of a gap, five wave lengths or more in width, wave heights (as Mr. Johnson suggest) may be determined simply by the application of the diffraction diagram for the semi-infinite breakwater to each of the two arms of the breakwater. At distances very large compared to the gap width, however, the two diffraction patterns appear to be no longer independent of each other. It then becomes advisable to construct a diffraction diagram for a gap as in Fig. 13, or to use some method that will achieve the same purpose.

In this connection, a modified Morse-Rubinstein curve may be used, in which the curve for the proper approach angle and for a gap of 3.0 L (the largest for which the curves are plotted) is used with only its scale altered. This adoption is made because the curves for intensity distribution for very large openings change but little in geometrical form from the long, slim loops of the curves of 3.0 L. The new scale is such that the maximum intensity factor is equal to the square of the gap width in wave lengths. When incidence is oblique, the opening size to be squared is the projected gap width, or—as Mr. Johnson refers to it—the "imaginary equivalent gap." With this modified curve, the wave height at a particular point is computed in the usual manner, and the method has been found satisfactory for all except the very acute approach angles.

J. W. JOHNSON,[48] M. ASCE.—In the short time since the writer's paper was submitted for publication additional research and study have been made on many of the problems presented in the paper. A brief summary of these developments is presented here.

The theory and extent of field observations on the generation and decay of wind waves have been extended, with the result that wave characteristics can be estimated with a much better degree of accuracy than was previously possible.[49] For the benefit of the practicing engineer these data have been summarized in convenient charts which permit the making of rapid estimates of wave characteristics from wind data.[7] Special problems, such as the forecasting of waves generated by near-coastal storms, have been discussed in detail in the literature.[50]

In connection with wave refraction on a shoaling bottom, considerable progress has been made in the improvement of the orthogonal method for the

[48] Prof. of Hydr. Eng., Univ. of California, Berkeley, Calif.

[49] "The Generation and Decay of Wind Waves in Deep Water," by C. L. Bretschneider, *Transactions* Am. Geophysical Union, Vol. 33, No. 3, June 1952, pp. 381–389.

[7] "Revised Forecasting Relationships," by C. L. Bretschneider, *Proceedings*, Second Conference on Coastal Eng., Council on Wave Research, The Eng. Foundation, 1952, pp. 1–5.

[50] "Near-Coastal Storms and Associated Waves," by D. K. Todd and R. L. Wiegel, *Transactions*, Am. Geophysical Union, Vol. 33, No. 2, April, 1952, pp. 217–225.

preparation of refraction diagrams. This work has been directed toward drawing orthogonals seaward from the shore[51,52] as well as deriving refraction coefficients directly from a single orthogonal.[53] Some work has been done on the comparison of observed wave directions with those obtained by means of a refraction diagram.[54] Besides the study of refraction caused by underwater topography, both theoretical and experimental work has been completed on refraction by currents.[55,56] The problem of wave reflection—both at structures[57] and in the surf zone[58]—has been investigated. To a varying extent, wave reflection is involved in those problems that are concerned with the damping action when waves pass over a submerged barrier[59] or through a pile structure.[60]

The more recent work on wave diffraction at breakwater gaps has been presented by Mr. Stelzriede. Little can be added to his discussion other than to point out that wave diffraction diagrams for breakwater gaps of various widths have been prepared and assembled into convenient form for the design engineer.[41] These diagrams were computed by the method of John H. Carr, J.M. ASCE, and Mr. Stelzriede[36] for relatively narrow gaps and by the procedure of F. L. Blue, Jr., and the writer[35] for the wider gaps. These diagrams pertain to gaps ranging in width from ½ wave length to 5 wave lengths, with the direction of wave approach normal to the gap. Diagrams also are provided to permit the preparation, by interpolation, of diffraction diagrams for any specific width. This simplified procedure for constructing diffraction diagrams is acceptable in the majority of design problems in which the accuracy with which the design wave data are known usually does not justify great refinement.

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[51] "A Method for Drawing Orthogonals Seaward from Shore," by Thorndike Saville, Jr., *Bulletin*, Beach Erosion Board, Corps of Engrs., Washington, D. C., Vol. 5, No. 4, October 1, 1951, pp. 1–6.

[52] Discussion by Kenneth Kaplan of "A Method for Drawing Orthogonals Seaward from Shore," by Thorndike Saville, Jr., *ibid.*, Vol. 6, No. 1, January 1, 1952, pp. 18–21.

[53] "Wave Intensity Along a Refracted Ray," by W. H. Munk and R. S. Arthur, *Wave Report No. 95*, Scripps Inst. of Oceanography, La Jolla, Calif., June 1, 1951 (publication pending).

[54] "Comparison of Observed Wave Direction with a Refraction Diagram," by D. R. Forrest, *Bulletin*, Beach Erosion Board, Corps of Engrs., Washington, D. C., Vol. 5, No. 2, April 1, 1951, pp. 24–25.

[55] "Refraction of Shallow Water Waves: The Combined Effect of Currents and Underwater Topography," by R. S. Arthur, *Transactions*, Am. Geophysical Union, Vol. 31, No. 4, August, 1950, pp. 549–552.

[56] "Breaking of Waves by an Opposing Current," by Y-Yuan Yu, *ibid.*, Vol. 33, No. 1, February, 1952, pp. 39–41.

[57] "Reflection of Solitary Waves," by J. M. Caldwell, *Technical Memorandum No. 11*, Beach Erosion Board, Corps of Engrs., Washington, D. C., 1949.

[58] "Total Reflection of Surface Waves by Deep Water," by J. D. Isaacs, E. A. Williams, and C. Eckart, *Transactions*, Am. Geophysical Union, Vol. 32, No. 1, February, 1951, pp. 37–40.

[59] "The Damping Action of Submerged Breakwaters," by J. W. Johnson, R. A. Fuchs, and J. R. Morison, *ibid.*, Vol. 32, No. 5, October, 1951, pp. 704–718.

[60] "Damping of Water Waves by Vertical Circular Cylinders," by R. D. Costello, *ibid.*, Vol. 33, No. 4, August, 1952, pp. 513–519.

[41] "Generalized Wave Defraction Diagrams," by J. W. Johnson, *Proceedings*, Second Conference on Coastal Eng., Council on Wave Research, The Eng. Foundation, 1952, pp. . 6–23

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